TEN YEAR PERFORMANCE EVALUATION OF UNBONDED CONCRETE OVERLAY AND JOINTED PLAIN CONCRETE PAVEMENT: A TORONTO CASE STUDY

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ABSTRACT

Heavy, slow moving traffic can be extremely damaging to asphalt pavements. The City of Toronto was observing the rapid deterioration of the pavements at an urban intersection with high volumes of transit bus traffic. The heavy traffic was causing severe rutting and other safety concerns. Despite regular maintenance and rehabilitation interventions, the distresses were regularly recurring.

In collaboration with the Cement Association of Canada, the City of Toronto elected to rehabilitate the high traffic intersection of Bloor Street and Aukland Road using Portland cement concrete materials in order to mitigate the existing problems. As part of this project, the city constructed its first unbonded concrete overlay and reconstructed an adjacent area as a conventional Jointed Plain Concrete Pavement. The rehabilitation activities were completed during the summer of 2003. Owing to the trial nature of these rehabilitation treatments in Toronto, instrumentation was installed by University of Waterloo researchers to monitor and evaluate the long-term performance of the rehabilitated pavements.

This paper presents an overview of the existing conditions, design, construction and instrumentation of the Bloor and Aukland site and a ten year performance evaluation of the rehabilitated pavements.

The results of this study show that concrete overlays and inlays are excellent rehabilitation options for urban pavements subjected to high volumes of heavy traffic. Both the unbonded overlay and Jointed Plain Concrete Pavement sections have demonstrated excellent performance to date. The pavements are in very good condition visually, ride quality remains excellent and the recurrence of the regular rutting and shoving problems that were being observed prior to rehabilitation has been mitigated. Significant remaining life is expected from the concrete pavement sections at Bloor and Aukland.

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1. INTRODUCTION

The City of Toronto was observing the rapid and repeated deterioration of asphalt pavements at a busy urban intersection. The high volumes of heavy, slow moving bus traffic were quickly causing extensive pavement distress. In collaboration with the Cement Association of Canada, the City of Toronto elected to rehabilitate the high traffic intersection of Bloor Street and Aukland Road using Portland cement concrete materials in attempt to mitigate the recurring problems. As part of this project, the city constructed its first unbonded concrete overlay on Bloor Street West and placed a full depth Jointed Plain Concrete Pavement inlay on the adjacent area on Aukland Road. This rehabilitation was completed in the summer of 2003. The University of Waterloo installed pavement instrumentation to measure pavement responses and has been regularly monitoring the long-term performance of the rehabilitated pavements (1).

This paper presents an evaluation of the pavement rehabilitation strategies using Portland cement concrete that were implemented. This paper outlines the existing conditions, design, construction and instrumentation of the Bloor and Aukland project, as well as presents details about the pavement's performance for the first ten years of service.

2. PROJECT BACKGROUND

The intersection of Bloor Street and Aukland Road, located in west Toronto, is subjected to very heavy traffic loadings. Bloor Street is a four-lane major east-west arterial road with an Average Annual Daily Traffic (AADT) of over 30,000 vehicles and high peak hourly volumes (approximately 1000 vehicles and in excess of 15 buses). It meets Aukland Road, a short north-south major collector road, at a T-intersection. Aukland Road leads directly into the nearby Toronto Transit Commission's (TTC) Kipling subway station, located approximately 500 metres south, as indicated in Figure 1. Many TTC and MiWay (formerly Mississauga Transit) bus routes travel along Bloor St. and turn onto Aukland Rd to travel to and from the subway station. In the first ten years of service, an estimated 3.5 million Equivalent Single Axle Loads (ESAL) have been imparted by transit buses alone. An ESAL, as defined by the American Association of State Highway and Transportation Officials (AASHTO), is equivalent to 80 kN (18 kips) (2). The AASHTO pavement design procedure uses the ESAL concept to convert mixed traffic of various wheel loads and axle configurations to a standard load for easy comparison and analysis.

The high volumes of heavy transit bus traffic travelling through this intersection led to frequent pavement deterioration beyond acceptable levels. Furthermore, since many of the vehicles travelling through the intersection were slowing to turn or stopping for the traffic signal, the damage imparted to the pavement was greater.

The results of a 2003 visual condition survey showed moderate rutting and shoving in the curb lanes on Bloor Street, near the stop bars. Frequent, severe reflective cracking was also apparent. Very severe rutting (up to 150 mm in depth) was observed on Aukland Road. Shoving was also occurring at the stop bars on Aukland Road. Furthermore, numerous asphalt patches (utility cuts) along both roadways had deteriorated and were negatively impacting ride quality (1).

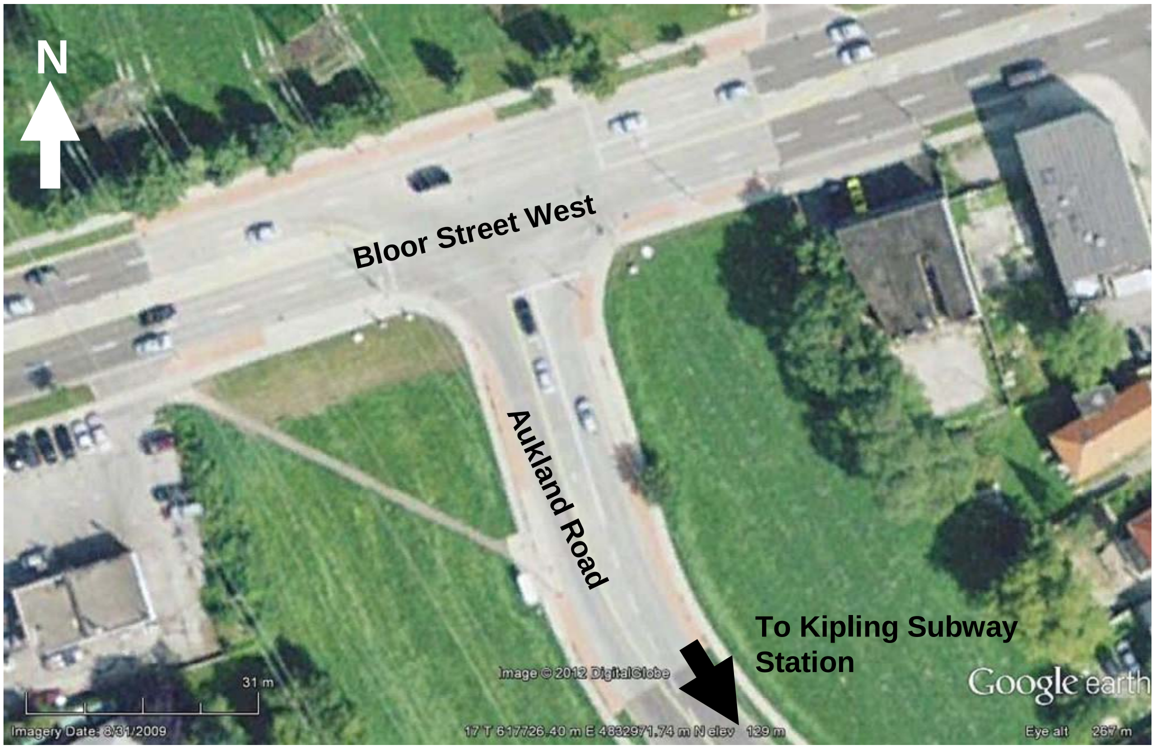

FIGURE 1 Overall plan of Bloor and Aukland intersection (3).

The recurring performance issues had forced the City of Toronto to frequently intervene with "mill and overlay" treatments to address safety concerns. It was apparent that traditional maintenance and rehabilitation treatments were not addressing the underlying issues and a more permanent solution was required. In 2003, the City of Toronto, in collaboration with the Cement Association of Canada, proceeded to rehabilitate the intersection using Portland cement concrete materials. As part of this pilot project, an unbonded concrete overlay was constructed on Bloor Street and part of Aukland Road was reconstructed as a full depth concrete pavement (1).

Although they make up a small percentage of the typical urban traffic mixes, buses can be very damaging. A typical 12.2 metre (40 foot) transit bus under typical passenger loads imparts approximately 2.6 ESALs per pass, whereas 18.3 metre (60 foot) articulated buses will impart about 3.4 ESALs. At peak periods where buses are under crush loads, conventional 12.2 metre buses will impart about 3.4 ESALs and 18.3 metre articulated buses, more than 5 ESALs (4). Comparatively, based on AASHTO Load Equivalency Factors, a typical passenger car has an ESAL impact of about 0.0004, many orders of magnitude fewer than buses or trucks (2).

3. PAVEMENT REHABILITATION WITH PORTLAND CEMENT CONCRETE

The rutting of asphalt pavements in urban areas, particularly at intersections, creates numerous safety concerns. Pavement rutting can reduce frictional characteristics due to flushing or water ponding. Lane changes can potentially become dangerous and vehicles can lose control, particularly during periods of poor weather. The ruts can also make snow removal more difficult. It is recommended that these safety concerns be addressed as soon as possible to mitigate the possible impacts on the safety of drivers, vehicles and pedestrians (5).

Unbonded concrete overlays, typically 150 to 275 mm thick, have been used as an effective rehabilitation solution for moderately to severely distressed pavements (6). This type of overlay can be constructed over existing concrete, asphalt or composite pavements. The existing pavement structure, albeit having some structural deterioration, serves as a base layer for the new concrete pavement placed on top. The concrete overlay restores ride quality and serviceability, while also providing the additional structural capacity required for future traffic loads (7).

Unbonded overlays over existing concrete pavements require a separation interlayer to prevent reflective cracking and premature failures (8). The interlayer, commonly a thin lift of asphalt concrete, provides a shear plane for differential movements and prevents the different concrete layers from becoming bonded together. With the inclusion of the interlayer, only minimal pre-overlay preparation is required (7). Significant cost savings can be incurred by avoiding the need to remove the existing pavement and the earlier investment in the original pavement remains intact (6).

Rigid pavements exhibit numerous advantages in areas subject to heavy, slow-moving traffic. They are virtually immune to rutting and shoving and have minimal maintenance requirements (6). The Transportation Association of Canada's new Pavement Asset Design and Management Guide suggests that 25+ years of service can be expected from unbonded concrete overlays (9).

4. DESIGN

A local engineering consultant was retained to carry out a geotechnical investigation and develop pavement designs for the intersection rehabilitation project.

The results of the field program revealed that the existing pavement on Bloor Street consisted of a composite structure (asphalt over concrete). It comprised of 80 mm of HL1 hot mix asphalt concrete (HMA), 200 mm of Portland cement concrete (PCC) base and 100-150 mm of granular base over a silty clay subgrade. The existing pavement on Aukland Road was a flexible structure, consisting of 190 mm hot mix asphalt concrete (40 mm HL1 over 150 mm HL8) over top of a 250 mm granular base on a silty clay subgrade.

Rehabilitation alternatives using Portland cement concrete materials were developed. Based on the existing conditions and anticipated traffic loadings, the recommended alternative was a 150 mm unbonded concrete overlay of the existing concrete base for an 85 metre long section of Bloor Street. A 63 metre long section of Aukland Road was reconstructed as a conventional Jointed Plain Concrete Pavement (JPCP), 225 mm thick. The existing and new pavement designs are illustrated in Figure 2.

As part of the University of Waterloo's involvement, instrumentation to assess the long-term performance of the rehabilitation strategies was installed in the new pavement layers. An instrumentation plan was devised to monitor the pavement responses of interest associated with the bus traffic and environmental effects.

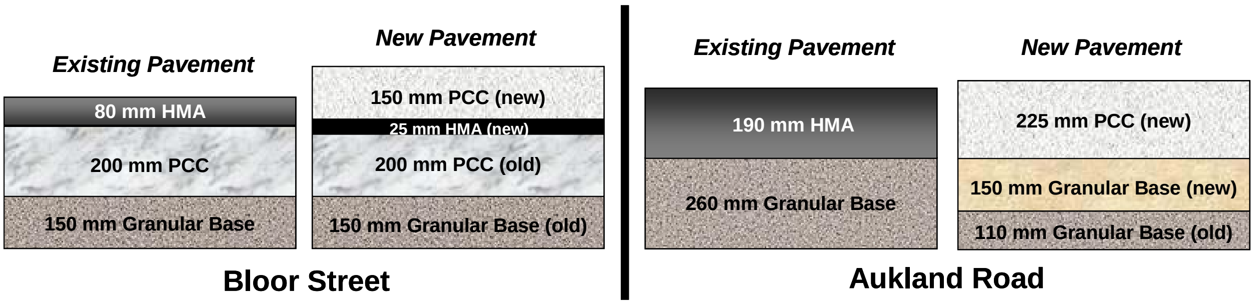

FIGURE 2 Existing and new pavement designs.

5. CONSTRUCTION

The rehabilitation activities were completed in a one month period. Construction was staged in order to maintain partial access to traffic through the busy intersection and reduce delays for the travelling public. The concrete pavement was placed over the course of two weekend closures in July 2003 in order to minimize delays.

On Bloor Street, the existing asphalt layer was removed by milling. Cracking in the underlying concrete base were routed and sealed and the deteriorated utility cuts were repaired with full depth concrete patches. Once the concrete base was prepared, a slow-setting asphalt emulsion tack coat was placed, followed by a 25 mm thick lift of high stability HL3 asphalt concrete, prior to placement of the new concrete overlay. Once the asphalt had sufficiently cooled, formwork was installed and the 150 mm thick concrete slab was placed on top.

Contraction joints were cut in a grid pattern at a short spacing of 1.5 metres. Joints were cut as soon as the concrete had set (within four to twelve hours) using a wet concrete saw to a depth of one-fourth of the thickness of the new concrete slab. Although not required in all overlay projects, dowel bars (25 mm in diameter by 400 mm long) were placed in turning locations and stopping areas to provide additional reliability from slow-moving or static vehicles. Dowel baskets were installed on the asphalt interlayer prior to the placement of the concrete.

On Aukland Road, the existing distressed asphalt concrete was removed, as was the top 150 mm of the existing granular base. The removed base material was replaced with fresh granular material, compacted and re-graded. The new 225 mm concrete slab was then placed. Full lane width transverse contraction joints were cut at a 4.5 metre spacing. The transverse joints of the Aukland Road pavement closest to the intersection were dowelled as well, in the same fashion as on Bloor Street.

During the first weekend closure, the eastbound lanes of Bloor Street West were paved, along with the centre lane of Aukland Road. This stage was constructed using fast track methods using high early strength concrete (24 MPa in 72 hours). The newly constructed lanes were re-opened to traffic on Monday morning. The following weekend, the westbound lanes of Bloor Street West and the outside lanes of Aukland Road were constructed using conventional concrete with a minimum strength of 32 MPa.

6. INSTRUMENTATION

Strain gauges were placed in the new concrete pavement layers to measure pavement responses over time in order to validate the pavement designs. Vibrating wire embedment strain gauges, manufactured by the Slope Indicator Company, were installed at various locations on both Bloor Street and Aukland Road. The sensor locations were strategically selected to capture the effects of accelerating, slowing and turning traffic, as well as the overall effects due to environmental changes. Seven gauges were installed on Bloor Street and five were placed on Aukland Road.

The vibrating wire strain gauges are capable of capturing the long-term effects of environmental loads, e.g. thermal expansion/contraction, shrinkage, curling and warping, as well as the cumulative effects of repeated traffic loadings. These sensors have an integrated thermistor to record temperature changes in the concrete as well.

To gain a complete picture of pavement responses, sensors were placed in different lanes and in both wheelpaths on both roadways. The depth of the sensors was also varied. Most sensors are located at 50 mm below the top of concrete, but three were also placed at the bottom of the concrete layer. The sensor arrangement is detailed in Table 1 and illustrated in Figure 3.

TABLE 1 Sensor Location and Descriptions

Sensor	Street Name	Lane Description	Depth below PCC Surface (mm)	Wheelpath	Operational after 10 years in service?
1	Bloor Street	WBD	50	Right	Yes
2		WBD	150	Right	Yes
3		WBD	50	Left	Yes
4		EBP	50	Right	No
5		EBD	50	Left	Yes
6		EBD	50	Right	No
7		EBD	150	Right	No
8	Aukland Road	SBD	50	Right	Yes
9		SBD	225	Right	Yes
10		SBD	50	Left	Yes
11		NBT	50	Right	No
12		NBD	50	Right	No

WBD – Westbound Driving Lane; EBP – Eastbound Passing Lane; EBD – Eastbound Driving Lane; SBD – Southbound Driving Lane; NBD – Northbound Driving Lane; NBT – Northbound Turning Lane

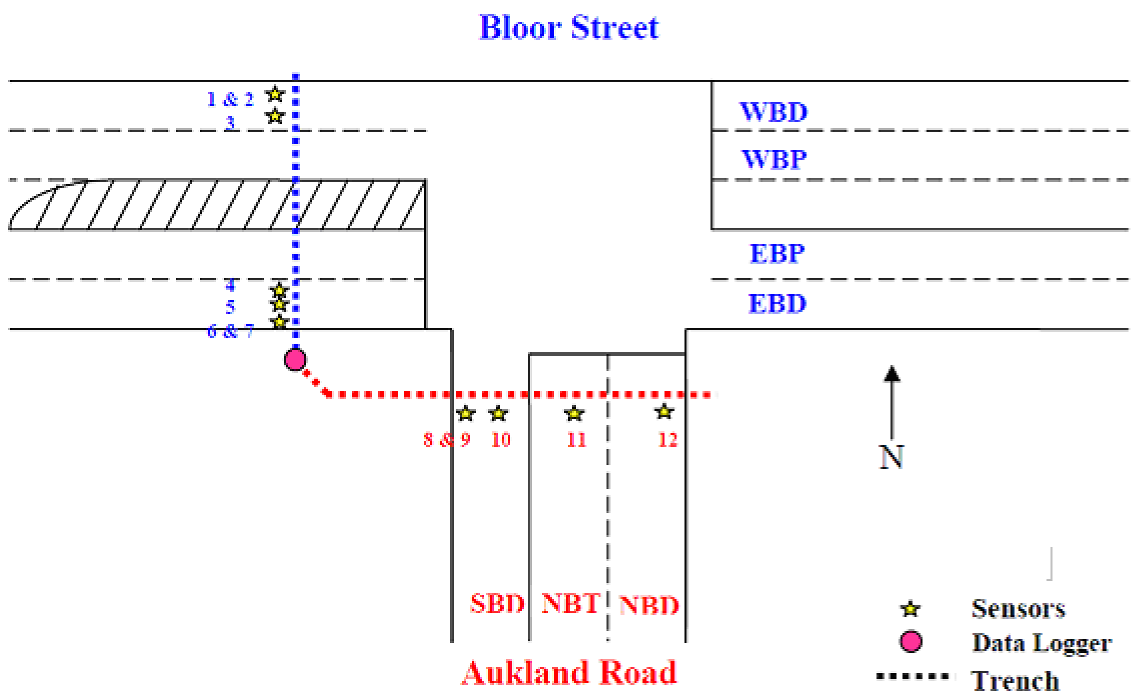

FIGURE 3 Instrumentation layout.

During construction, members of the University of Waterloo research team were present to install sensors and the associated wiring. The strain gauges were attached to steel chairs, as shown in Figure 4. The wiring was fed through PVC conduit for protection, which was buried in trenches below the pavement. The sensors are connected to a solar-powered Campbell Scientific datalogger, housed in a weatherproof steel enclosure on the southwest corner of the intersection. Sensor data is recorded hourly and has been regularly collected since construction was completed.

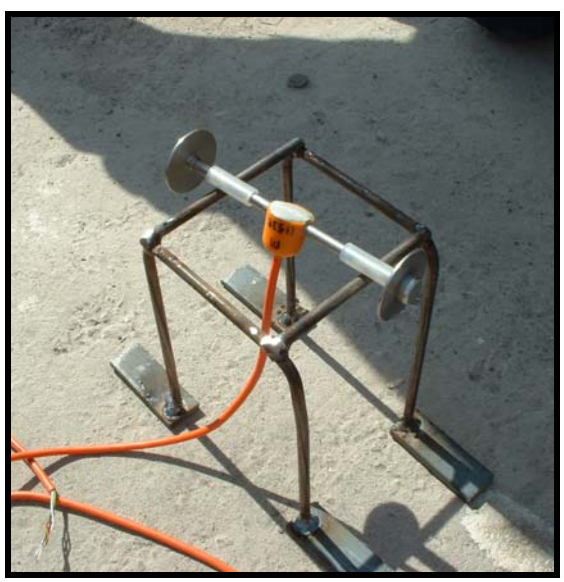

FIGURE 4 Typical strain gauge installation before paving.

7. POST-CONSTRUCTION MONITORING AND PERFORMANCE EVALUATION

Sensor Data Collection and Analysis

The most obvious trend observed in the strain data is a clear daily variation in strain, corresponding with a daily temperature cycle. The measured strains increase as the concrete heats up and expands with rising temperatures and exposure to solar radiation during the day and decrease as the pavement cools and contracts overnight.

Seasonal trends have been observed from year to year as well. The largest strains are observed in the winter season, which is likely due to the drastic changes in temperatures. Although Toronto's average daily temperature in January is -4.5ºC, the city can experience temperatures ranging from -33ºC to 16 ºC (10). The measured strains continue to decrease throughout the year, with the lowest strains being observed in the fall.

Throughout the ten year period, a general trend of increasing compressive strains has been observed in the unbonded overlay on Bloor Street, both at the top and bottom of the overlay layer. This trend is illustrated in Figure 5, which compares strain data from the first, third and ninth years of service. The boxplots present the maximum, third quartile, median, first quartile and minimum strain values for each year. Strain values greater than zero are tensile; those less than zero are compressive.

The trend of increasing compression at the top surface is no surprise; however, the bottom sensors are expected to be measuring tensile strains. Unbonded overlays are designed to have the overlay slab and existing slab bend separately under traffic and environmental loads due to the placement of a separation layer, shown in Figure 6.

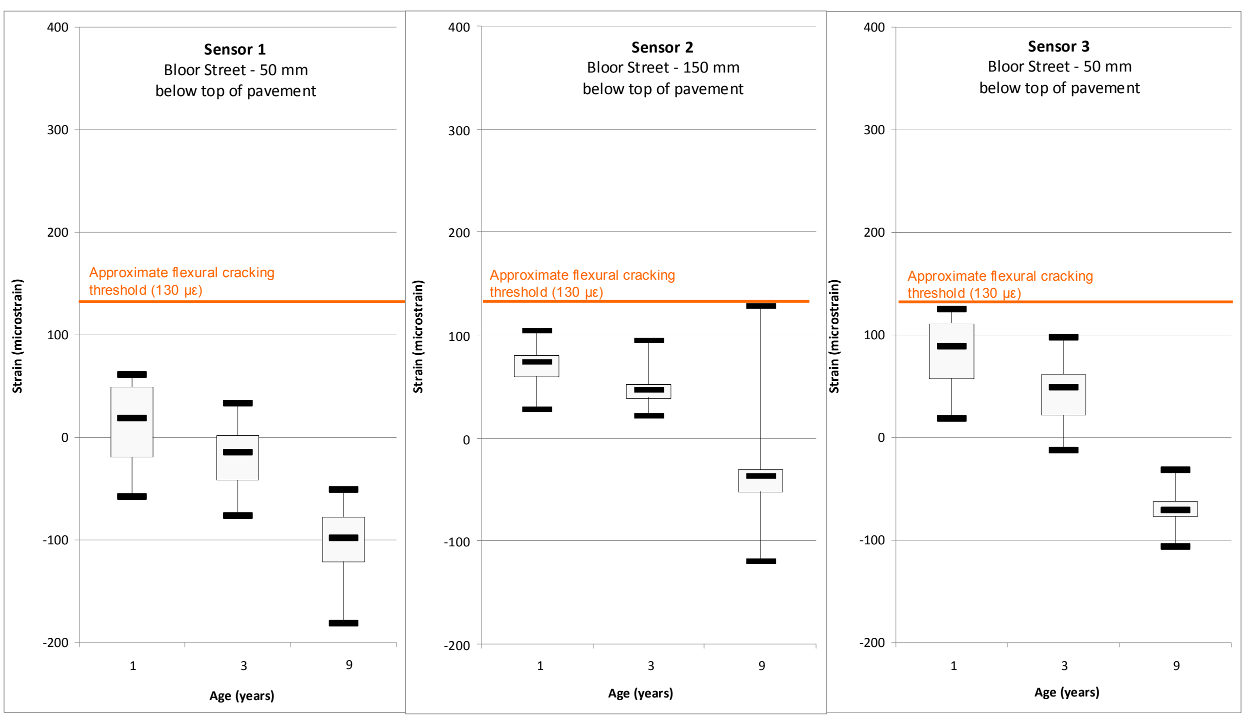

FIGURE 5 Comparison of strains in unbonded overlay after 1, 3 and 9 years of service.

FIGURE 6 Comparison of unbonded and bonded overlay strain profiles (11)

However, preventing a bond between the two concrete layers cannot always be accomplished. It is possible that this may be the case with the Bloor Street overlay. The evidence of compressive strains throughout the thickness of the overlay may indicate that both slabs (old and new) are behaving monolithically and that the neutral axis falls in the old slab. The bonding of the layers can add additional structural capacity to the pavement, but is generally undesirable because it may allow reflective cracking to occur (6). By and large, the strains measured in the overlay section remain fairly low, i.e. well below cracking thresholds. The threshold for flexural (tensile) crack formation in a 30 MPa concrete is approximately 130 microstrain (12). Consequently, considerable remaining pavement service life is expected.

In the Jointed Plain Concrete Pavement (JPCP) section on Aukland Road, the average strain reading for sensor eight (southbound lane, top of concrete) saw a slight decrease between years one and three, and remained fairly consistent through the ninth year of service, not showing much change over time, as seen in the boxplots in Figure 7. The same trend of decreasing strain was observed in sensor nine (southbound lane, bottom of concrete) between years one and three. However, between years three and nine, a significant increase in strain, that is a growth in tensile strains, was observed, also seen Figure 7. The increase in tensile strains is expected at the bottom of the slab as vehicular loads will induce tensile stresses and the damage accumulates with repeated loadings. However, the year nine strain magnitudes are somewhat suspect since they are very high.

Strains of this magnitude exceed the tensile cracking limit of concrete and would have likely resulted in the development of cracking on the surface. However, no distress is visible in the vicinity of the sensor. The probable explanation is the degradation of the sensor over time or damage to the sensor or its wiring. The development of zero drift is also a possible source of error. Zero drift is a condition where the measured strain values changes for reasons other than actual changes in strain, such as creep of the vibrating wire (13). Nevertheless, the trend in strain observed in sensor nine is still valid and overall, the changes in strain observed in the JPCP section satisfy expected trends.

As of April 2013, only seven of the twelve gauges originally installed remain operational. Some of the non-functional sensors started providing erroneous readings soon after construction, whereas others became defective in later years. The erroneous or missing data has been excluded from any analyses. The loss of working strain gauges makes a complete analysis more difficult, because some comparisons of possible interest are no longer possible. Nevertheless, the embedded instrumentation continues to provide valuable information relating to the behaviour of the concrete under environmental and vehicular loadings.

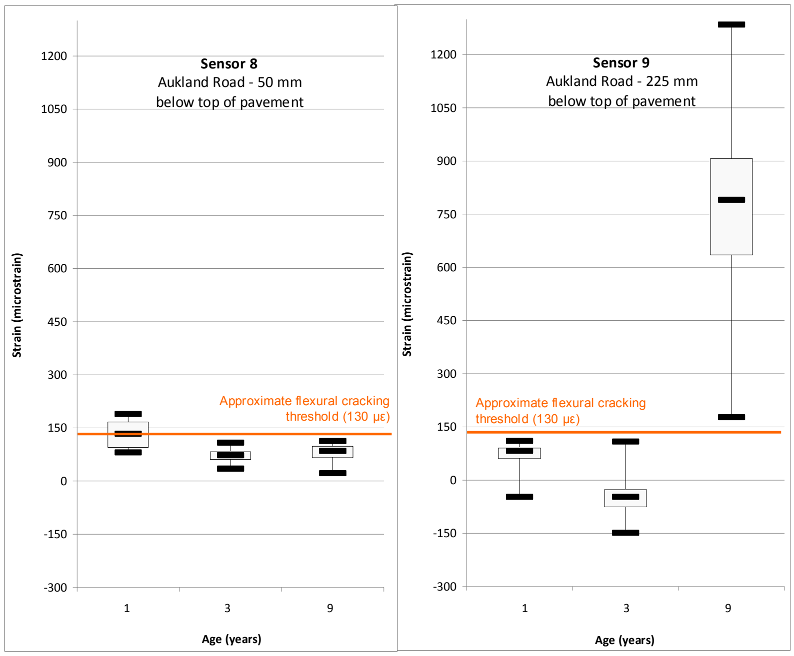

FIGURE 7 Comparison of strains in JPCP after 1, 3 and 9 years of service.

Visual Condition Survey

Visual condition surveys of the concrete sections have been performed regularly. The results of the most recent condition survey, performed in April 2013, show that both rehabilitated pavements remain in very good condition after ten years of service. Distresses are infrequent and generally low in severity.

Some transverse joints exhibit ravelling and minor spalling. The longitudinal joints between the pavement and curb and gutter also display occasional spalling as well, likely attributable to edge restraint effects. The settlement and movement of catchbasins has resulted in some cracking in the adjacent concrete, as shown in Figure 8. The improved isolation of the drainage appurtenances could reduce or prevent this damage. The most significant distress is two cracked slabs near the north-south crosswalk on the east side of the intersection, seen in Figure 9.

Overall, the ride quality of both sections remains excellent. The narrow width of the sawcuts in the overlay prevents the occurrence of “joint slap” noise, despite the short joint spacing, which results in a much greater joint frequency than most conventional concrete pavements.

Despite the marginal surface condition of the overlaid concrete base, none of the pre-existing cracks or other distresses have reflected upwards into the overlay layer. The asphalt interlayer has successfully prevented the occurrence of any reflective cracking.

FIGURE 8 Cracking near catchbasin.

FIGURE 9 Cracked slabs in crosswalk area.

As well, the recurring rutting and shoving problems that were being observed prior to rehabilitation have been mitigated. The implementation of Portland cement concrete, a rigid material, as the pavement material in this area has eliminated their recurrence.

It should also be noted that no maintenance or rehabilitation has been required for the Bloor St. and Aukland Rd. sections since construction.

8. SUMMARY AND CONCLUSIONS

The results of this study demonstrate that concrete overlays and inlays are excellent rehabilitation options for urban pavements subjected to high volumes of traffic.

The Bloor Street section, earning the distinction of the first unbonded overlay in Toronto, has proven itself as a feasible rehabilitation treatment for distressed concrete or composite pavements. The overlay section has shown excellent performance in its first ten years of service, with no major functional or structural issues of note to date. The recurring issues prior to rehabilitation, e.g. frequent rutting and shoving, have also been mitigated It is anticipated that the expected service life of 25+ years (9) will be met and potentially exceeded, improving the return on investment and further highlighting its cost-effectiveness.

The performance of the Aukland Road pavement also shows that the use of concrete inlays, such as this short section of JPCP, is a viable technique for mitigating the rutting and shoving of asphalt pavements at intersections, which is frequently observed in areas high volumes of heavy traffic, such as bus route. The concrete pavement, which does not deform under static or slow moving vehicles, maintains the safety characteristics of the roadway and averting the need for inconvenient and expensive maintenance work.

The embedded instrumentation has contributed much valuable information to the evaluation of these sections. For the most part, the measured strains remain low in both the unbonded overlay and the jointed plain section. The low strains are indicative of significant remaining life for both sections.

9. RECOMMENDATIONS

Continued monitoring of the experimental sections described herein is recommended. Ongoing data collection and evaluation will continue to provide additional valuable information for researchers as the test sections enter their second decade of service. The sensor data can be used to mechanistically model the behaviour of unbonded concrete overlays. This type of model can be used to predict future overlay performance and remaining life. Furthermore, the validation of the results obtained from the sensor data using the Mechanistic-Empirical Pavement Design Guide (MEPDG), now distributed as the AASHTOWare Pavement ME Design software, is also recommended.

Falling Weight Deflectometer (FWD) testing is also suggested to evaluate the current structural condition of the rehabilitated pavements. One round of deflection testing was performed prior to rehabilitation. This additional testing will help quantify the pavement’s current structural capacity and assist with evaluating remaining life.

10. ACKNOWLEDGEMENTS

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